In-Situ Wave Observations in the High Resolution Air-Sea Interaction DRI

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LONG-TERM GOALS

Ocean wave prediction models, based on a spectral energy balance, are widely used to obtain wind-wave forecasts and hindcasts on global and regional scales (e.g., Komen et al., 1994). However, these inherently stochastic models assume a Gaussian and homogeneous sea state and thus do not describe the nonlinear instability processes that can dramatically alter the structure of wave groups and produce anomalously large waves, also known as 'freak' or 'rogue' waves (e.g., Janssen, 2003). Fully deterministic modeling capabilities are now becoming available that incorporate these nonlinear effects and provide the detailed phase-resolved sea surface predictions needed in many applications. Concurrent with the development of new models, advances in radar remote sensing techniques are enabling the detailed observation of the sea surface on the scales of wave groups and individual waves. The long-term goal of this research is to test these emerging new models and measurement technologies in realistic sea states and use them to better understand and predict the wave group structure and occurrence of extreme waves in the ocean.

OBJECTIVES

- Observe the nonlinear evolution of wave groups in realistic broad-band sea states.
- Provide ground-truth data for testing the capabilities of ship-board wave radar systems.

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- Provide in-situ wave data for the verification of phase-resolving wave prediction models.

APPROACH

The primary goal of the High Resolution Air-Sea Interaction DRI is to advance observational and modeling techniques for monitoring the wave-resolved sea surface around a vessel. Field experiments will be conducted off the California coast, using the floating platform FLIP with a suite of meteorological and oceanographic instruments, airborne and ship-board radar systems, and an array of moored and free drifting buoys. Our proposed contribution to these experiments is an array of surface-following buoys that will be embedded within the footprints of FLIP-based, airborne and ship-board remote sensing systems. The array will cover a nominal area of about 15 by 15 km that spans the anticipated evolution scales of nonlinear wave groups.

The Datawell Directional Waverider (DWR) buoys that will be used in the experiments, are small surface-following buoys that measure vertical and horizontal water particle motion at the sea surface directly, from which time series of surface height and slopes can be extracted. The accuracy of these buoys is well established (e.g., O'Reilly et al., 1996) and their reliability in high sea states is attractive for deployments in the open ocean. We have successfully used DWR buoys in the recent ONR-sponsored SHOWEX (Ardhuin et al., 2003; 2007) and NCEX (Magne et al., 2006) experiments and believe they are well suited to conduct the proposed measurements in an energetic wave environment. To accommodate both high spatial resolution and flexibility in the array design and sampling scheme, we plan to use a combination of moored and free-floating DWR buoys. One of the larger (0.7 or 0.9 m diameter) DWR buoys will be moored within a few km of FLIP to obtain continuous in-situ surface wave measurements within the footprint of FLIP-mounted radar and other remote sensing systems. The remaining buoys (including the novel 0.4 m diameter mini-DWR buoys) will be deployed free-floating during the intensive phases of the experiments when ship-board radar measurements and aircraft over-flights take place. These buoys are deployed from the same vessel that collects the radar measurements, thus allowing for close coordination of the sampling schemes.

The tentative experiment plan, described below, uses nominally 6-8 buoys spanning a distance of 10-20 km that includes several wave groups. These measurements, together with other in-situ instruments deployed by other investigators (i.e. sensors mounted on FLIP) and remote sensing observations (ship-board and airborne radars) will allow for a detailed investigation of nonlinear wave evolution over scales of a few wavelengths to several wave groups. The free-floating buoys will be deployed upwind of FLIP, then allowed to drift for several hours (while being monitored), and retrieved downwind off FLIP. Numerous ship-board buoy deployments will be conducted during the 4-week-long experiment in concert with other ship-board measurements and aircraft over-flights. The deployment of the free-floating buoys can be adapted to the attendant weather (wind/swell) conditions, the configuration of ship-board and airborne radar systems, and data assimilation strategies employed in the numerical modeling efforts.

WORK COMPLETED

During FY09 we participated in the continued planning of the High Resolution Air-Sea Interaction DRI. During several meetings the plan for the main experiment was refined. This month-long experiment will take place during June 2010 in about 1200 m depth off the Central California coast. A

pilot experiment was conducted in June 2009 off the Southern California coast. Preliminary results of this field campaign are detailed below.

To optimize array design for observing wave group evolution, we use a forward-scattering angular-spectrum model [see e.g. Dalrymple & Kirby, 1988; Janssen et al. 2006]. This model presumes waves to propagate in a half plane, thus omitting back-scattered wave energy, or waves traveling at a larger than 90 degree angle with respect to the principal direction; it accounts for cubic nonlinearity that is believed to be the primary mechanism for nonlinear wave group evolution in deep water and the associated development of freak waves (Janssen, 2003).

Whereas weak nonlinearity of ocean surface waves can cause deviations from Gaussian statistics and an increase in likelihood of extreme wave heights, numerical simulations show that nonlinear wave-wave interactions in freely evolving random wave fields cause a directional broadening that stabilizes the wave field toward a near-Gaussian state, thus suppressing the development of 'freak' waves. On the other hand, when waves propagate through a sudden medium variation such as a spatially varying current or a seafloor topographic feature, this equilibrium may be upset and instabilities may develop, resulting in non-Gaussian statistics and an increased likelihood of extreme wave events. To investigate this hypothesis, we extended our numerical model to incorporate the combined effects of cubic wave nonlinearity and refraction induced by a weak lateral medium variation. Numerical model simulations of random waves propagating over a sheared current confirm that refractive focusing of wave energy can indeed cause a wave field to become unstable and develop strongly non-Gaussian statistics with an increased likelihood of extreme waves. Computations of waves propagating over a sea mount produce similar results with the development of large freak waves on the leeward side of the shoal (Janssen and Herbers, 2009).

RESULTS

In early June 2009 we participated in a week-long pilot experiment in deep water off the Southern California coast. We deployed a cluster of free-drifting buoys within the foot-print of the ship-board wave radar system operated by Dr. Eric Terrill's group (SIO). During this pilot experiment Dr. Qing Wang's group (NPS) collected ship-board meteorological data and Dr. Ken Melville's group (SIO) conducted overflights with airborne lidar and video systems.

Our main objectives during this field test were to (1) intercompare the performance of different buoys (i.e. accelerometer vs. GPS, larger vs. mini buoys), and (2) accurately track the buoys in space and time to facilitate integration with other data sets. Five Datawell DWR buoys were deployed, a 0.9 m diameter MarkII buoy equipped with an accelerometer package, tilt sensors and compass, two DWR-G7 buoys (0.7 m diameter) with a specialized GPS motion sensor that measures the Doppler shift in the GPS signal, and two DWR-G4 mini buoys (0.4 m diameter) that contain the same sensor as the DWR-G7 buoys. To track the buoy position in absolute space and time additional SBAS-accuracy GPS receivers were mounted externally on each buoy.

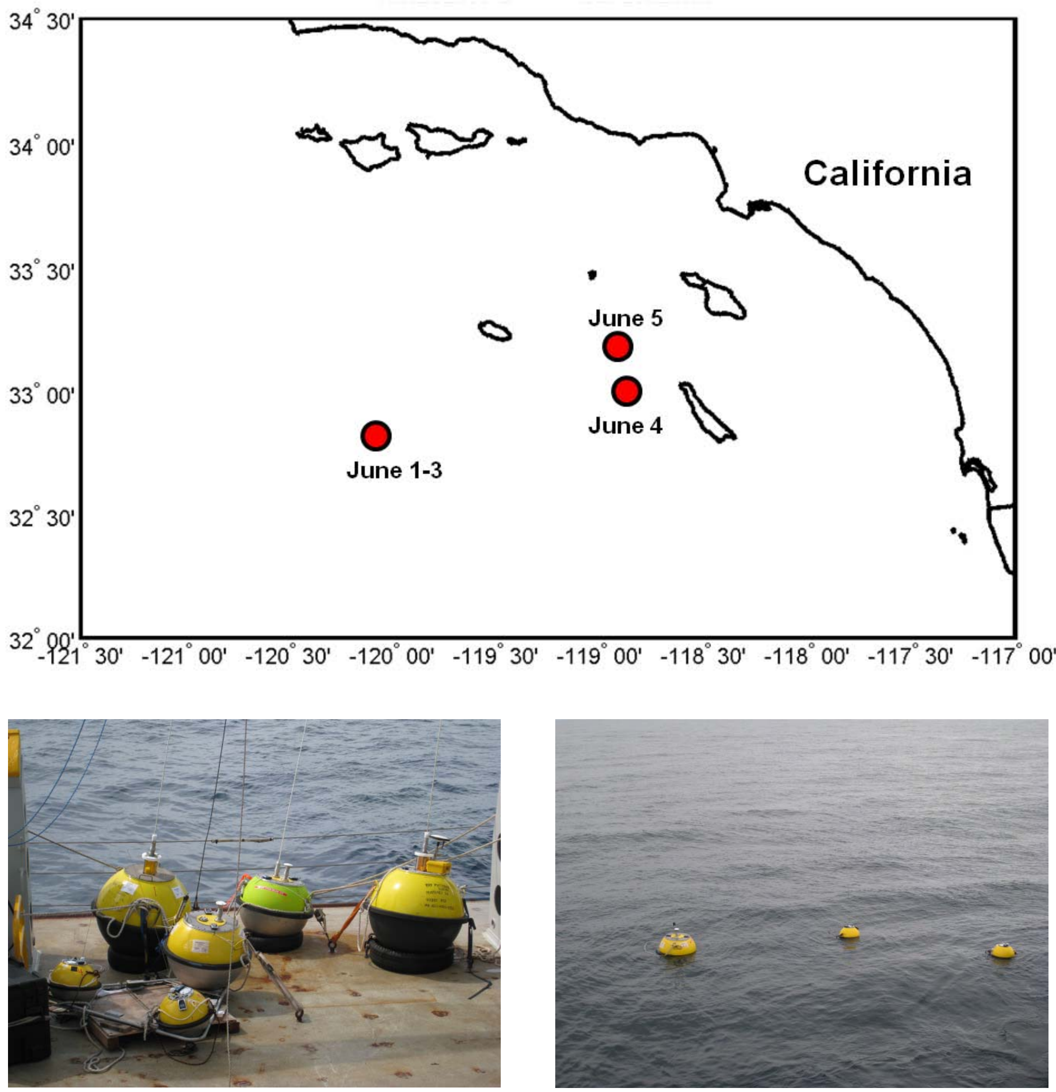

Figure 1. June 2009 Pilot Experiment. Upper panel: Deployment locations during the week-long experiment. Lower panels: photos of Directional Waverider Buoys (diameters 0.4, 0.7 and 0.9 m) before and during a deployment.

The data were collected during June 1-5 in deep water near San Nicholas and San Clemente Islands (Figure 1). Four to five drifting buoys were deployed in a small area and allowed to drift freely for periods of 2-6 hours. The long time series and close proximity of the buoys (maximum separation about 1 km) allow for a detailed comparison of wave statistics. Results for a deployment on June 3 are detailed in Figure 2. Wave conditions were benign with a swell dominated spectrum (peak period 14 s and significant wave height 0.9 m). All five buoys clearly resolve the three distinct wave systems traveling in different directions, and the spectral levels and mean directions are in excellent agreement across the entire wave spectrum. These comparisons (and those of the other deployments, not shown) demonstrate that the DWR-G7 and DWR-G4 buoys with GPS sensors provide frequency- and directional spectral wave measurements (colored curves) that are consistent those obtained with the more established MarkII buoy with a traditional accelerometer/tilt/compass measurement system (black curves).

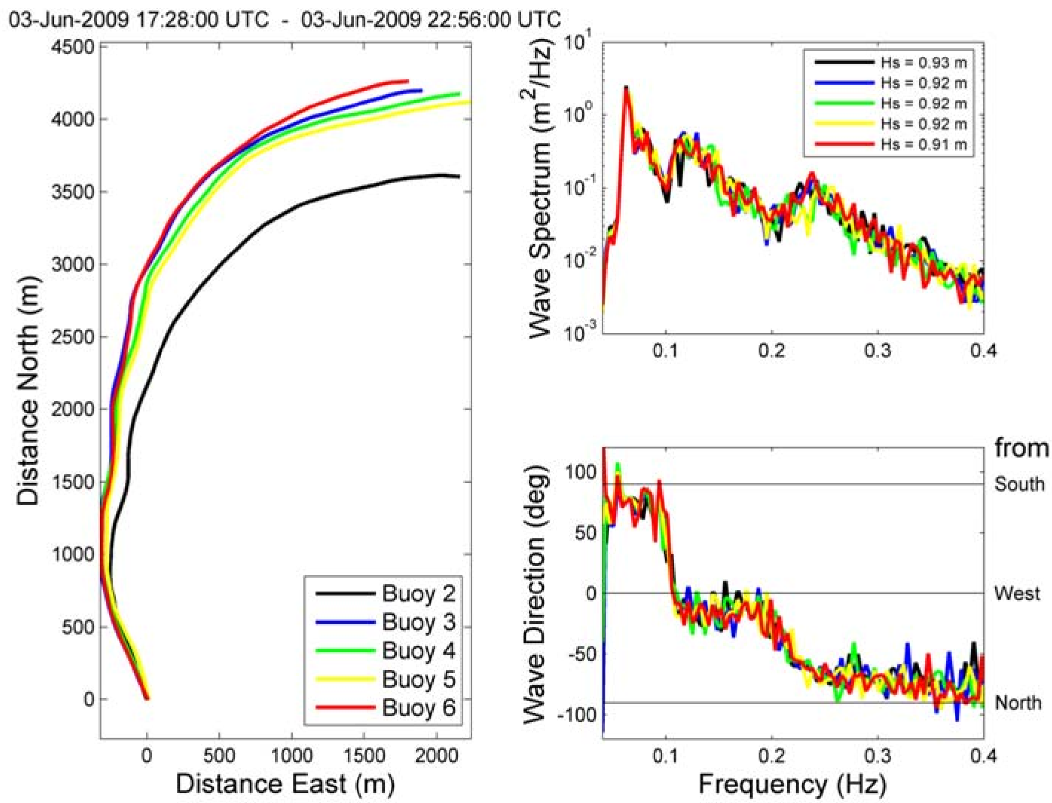

Figure 2. Drifting buoy wave observations during a 5 ½ hour period on June 3, 2009. Left panel: Drift tracks show the dispersion of a cluster of five buoys that were initially separated by less than 20 m. Right panels: Intercomparison of wave spectra (top) and mean wave directions vs. frequency (bottom). The buoys include an accelerometer-based 0.9 m MarkII buoy (black curves), and GPS-based 0.7 m DWR-G7 (blue and red) and 0.4 m DWR-G4 (green and yellow) buoys. Estimates of the significant wave height for each buoy are listed in the legend of the upper right panel.

Whereas it has been well established that surface-following buoys can yield reliable estimates of surface wave spectra, their capability to resolve the profiles of individual waves and wave groups has received less attention. In the HIRES pilot experiment and other field tests in Monterey Bay and Carmel Bay we investigated the fidelity of phase-resolved wave orbital displacement time series by comparing measurements of independent sensors on the same buoy. An example result from the pilot experiment is shown in Figure 3. Measurements of vertical and horizontal wave orbital displacements obtained with the Datawell MarkII buoy on June 3 (the Buoy 2 data shown in Figure 2) are compared with measurements from a GPS receiver mounted on the same buoy. The GPS measurements (red curves), obtained with a Magellan MobileMapper CX GPS receiver with an active external antenna mounted on the buoy, are absolute position measurements that were high-pass filtered to remove the buoy drift. The buoy measurements (blue curves) are derived from the autonomous Hippy motion sensor in the buoy, consisting of three-component accelerometers, tilt sensors and a compass. Hence, these two data sets are completely independent. The time series extracted from the buoy and GPS sensors are in excellent agreement and capture not only the dominant waves but much of the fine scale

structure in the vertical and horizontal wave orbital displacements.   Although the O(0.5-1 m) wave excursions in these benign wave conditions are smaller than the 2-5 meters absolute accuracy of the GPS system, the spectrum of GPS position errors is apparently dominated by much lower frequency fluctuations (e.g. atmospheric noise) thus enabling the detection of relatively small amplitude waves at wind sea and swell frequencies. These results, and similar other tests with the DWR-G7 and DWR-G4 buoys (not shown) demonstrate that small surface-following buoys can provide accurate measurements of the phase-resolved sea surface evolution, and that Lagrangian drifters equipped with relatively inexpensive SBAS-accuracy GPS receivers can provide high quality wave measurements.

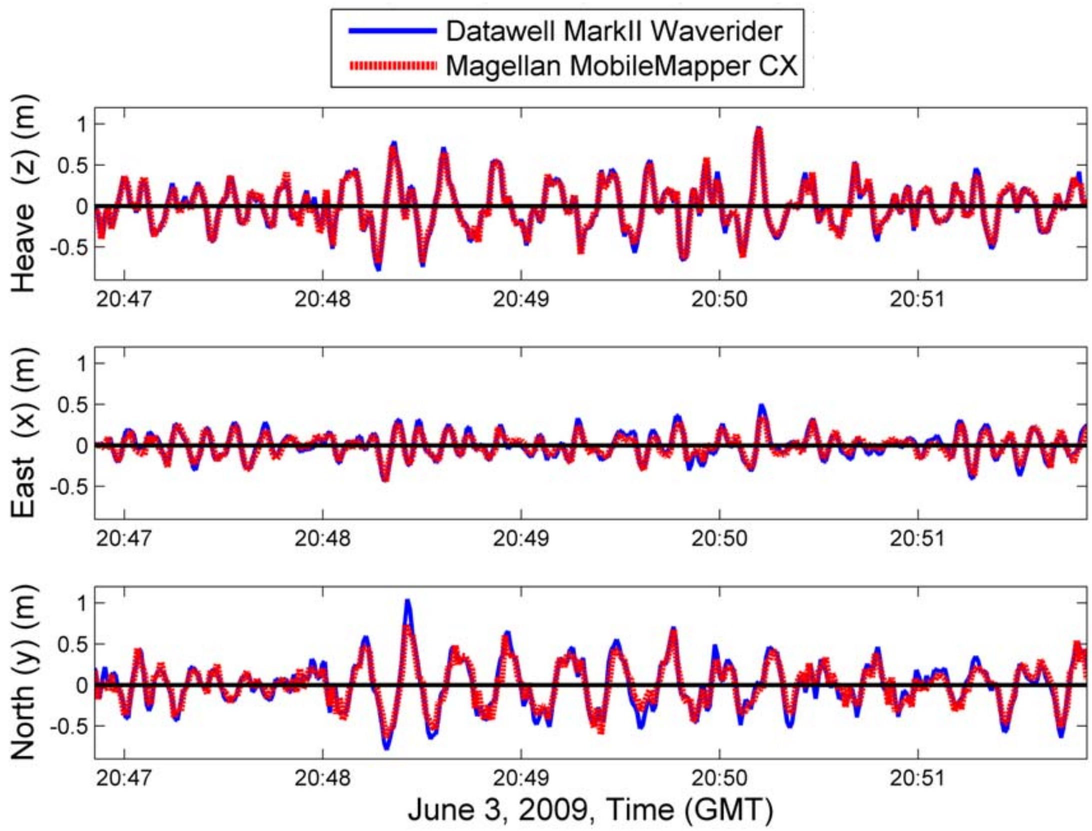

Figure 3. Example comparison of observations by MarkII buoy and GPS receiver mounted on buoys hull. From top to bottom: time series of vertical, east and north displacements. The excellent agreement of two completely independent sensors (i.e. an accelerometer/tilt/compass system versus a GPS system) demonstrates that highly accurate phase-resolved measurements of ocean surface waves can be obtained with small drifting buoys.

IMPACT/APPLICATIONS

This project will yield an improved understanding of ocean surface wave dynamics in deep water and a comprehensive verification of numerical models and radar remote sensing techniques in natural broad-band sea states. These results are critical in the future development of a system for routine monitoring of the wave resolved sea surface around a vessel.

RELATED PROJECTS

We are investigating ocean wave dynamics in shallow water environments in the ONR Coastal Geosciences Projects: Wave-Mud Interactions and the Seafloor Ripples DRI. While the focus in these projects is on the interactions of ocean waves with the seafloor, the numerical modeling approaches and measurement techniques are similar. In addition to these synergies, the combined deep- and shallow-water efforts will provide valuable insight in the role of finite-depth effects in nonlinear wave dynamics, and the associated wave group properties and extreme wave statistics.

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PUBLICATIONS

Janssen T. T., and T. H. C. Herbers, Nonlinear wave statistics in a focal zone, *J. Phys. Oceanogr.*, **39**(8), 1948-1964, 2009. [published, refereed]